

FY04 NEPP TRO – Sensor Technology: Near Infrared Avalanche Photodiodes

Heidi Becker

Jet Propulsion Laboratory, California Institute of Technology

The following document presents the state of JPL's investigation into the radiation response of near infrared avalanche photodiodes during the 2004 fiscal year.

The research in this document was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA), under the NASA Electronic Parts and Packaging Program, Code Q.

I. Rationale for Testing Near Infrared Avalanche Photodiodes

Deep-space optical communications is an active area of research at JPL. Optical communications is being pursued as an alternative to RF communications, because of the relatively low mass, volume, and power requirements and the potential for increased data rates. The emphasis of current deep-space optical communications research at JPL is in gaining ground-based receiver experience, as a precursor to space-based optical communications data receivers. Low noise, high quantum efficiency data detectors are also being investigated for current space-based ranging applications and optical communications technology demonstrations in space.

There is a strong interest in the use of avalanche photodiodes (APDs) as space-borne data receivers. APDs are an attractive receiver choice for photon-starved (low signal) applications, because their internal gain mechanism can improve signal to noise ratio. An optical receiver must also be appropriate for the laser wavelength being used. The near infrared is the preferred wavelength regime for deep space optical communications, largely due to the wavelengths of available laser technologies that meet the optical power requirements of a deep space optical link.

The NEPP FY03 Emerging Photonics task involved gamma and 51-MeV proton testing of several different silicon APD structures, including a near IR-enhanced Si APD appropriate for 1064 nm systems [1], [2]. Silicon detectors have a long-wavelength responsivity cutoff at 1.1 microns, which corresponds to the wavelength of its bandgap. Therefore, detectors made from materials with higher absorption coefficients at long wavelengths are necessary for near infrared applications above 1.1 microns.

The silicon APDs that were tested in FY03 showed sensitivity to radiation-induced increases in dark current and noise. It was also observed that differing degrees of damage could be correlated to structural differences in the tested technologies. In FY04 high speed InGaAs and Ge APDs, appropriate for 1300 and 1550 nm applications, were tested for their susceptibility to dark current degradation from proton and gamma irradiation. A description of our test methods and results follows.

II. Methods

A. Test Devices

Three APDs were selected for the study: two InGaAs APDs (the G8931-03 from Hamamatsu, and the C30645E from Perkin Elmer), and a germanium APD from Judson (J16A-18A-R100U). Key characteristics of the three devices are listed in Table I.

TABLE I
NEAR INFRARED AVALANCHE PHOTODIODES STUDIED IN FY04

APD Structure	Active Area Diameter	Cutoff Frequency	QE @ 1300nm	Dark Current (nA)
Hamamatsu <i>InGaAs</i>	30 microns	2 GHz	0.7	~ 6 (M=10)
PerkinElmer <i>InGaAs</i>	80 microns	1 GHz	0.85	~ 1.5 (M=10)
Judson <i>Ge</i>	100 microns	1.5 GHz	0.7	~300 (M=3)

All are high-speed APDs, with cutoff frequencies (the frequency at which the output signal power is down by 3 dB) between 1 GHz and 2 GHz. The quantum efficiency of all three devices is high at 1300 nm, and the InGaAs structures have particularly low dark current at a typical gain (M) of 10, making them good candidates for photon-starved applications in that wavelength regime.

B. APD Structure and Processes

Fig. 1 shows a basic APD structure. APDs use a reverse bias applied to a p-n junction. They operate in a fully depleted mode; the reverse bias creates a depletion region in the diode that extends from the junction through the absorption region where photons are absorbed. Absorbed photons create electron-hole pairs in the depletion region. Carriers are swept via drift toward a very high field region near the junction called the avalanche (multiplication) region. Here, carriers create additional e-h pairs through impact ionization, starting the chain reaction of avalanche multiplication (the internal gain mechanism of APDs).

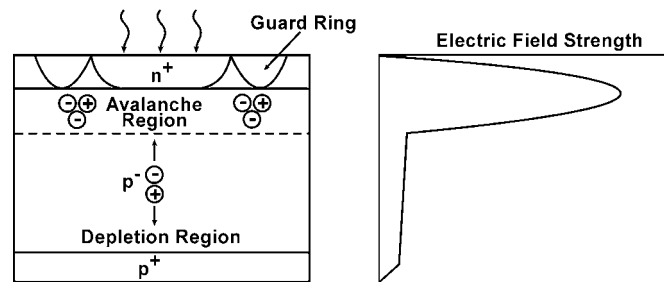


Fig. 1 Avalanche photodiode structure.

APD dark current has two components, bulk dark current (which is gain multiplied because it traverses the multiplication region) and surface dark current (which is not gain multiplied). Guard rings are a typical approach to control surface currents.

Radiation-induced changes in dark current are important to quantify, because dark current changes are an important component of such figures of merit as signal to noise ratio and noise equivalent power (NEP). The total spectral noise current of an unilluminated APD is given by:

$$i_n = [2q(I_{ds} + I_{db}M^2F)B]^{1/2} \quad (1)$$

where I_{ds} is the unmultiplied surface dark current, I_{db} is the gain-multiplied bulk dark current, M is the gain, F is the excess noise factor, and B is the noise bandwidth. Total dark current (I_d) is related to the parameters in (1) by:

$$I_d = I_{ds} + MI_{db} \quad (2)$$

Ultimately, increases in detector dark current (and, therefore, noise) increase the probability of bit error (BER) in digital communications, the exact degree of which is dependent on the encoding scheme in question [3], [4].

C. Experimental Procedure

Four samples of each InGaAs APD structure were irradiated at Crocker Nuclear Laboratory, UC Davis, using 63-MeV protons to a fluence of $2 \times 10^{12} \text{ p/cm}^2$. The devices were irradiated and characterized for changes in total dark current (I_d) (leakage current measured at operational voltages under unilluminated conditions), under a constant reverse bias. The voltage was that required for a pre-irradiation gain of approximately 10, and was approximately $0.95 V_{BR}$ (breakdown voltage) for the Hamamatsu APD and $0.89 V_{BR}$ for the Perkin Elmer APD. The mean values were 68.5V and 46.8V, respectively. The only exception was that one of the four Perkin Elmer samples was irradiated unbiased and characterized at $0.89 V_{BR}$; no significant difference in post-irradiation behavior was observed compared to the biased test samples. One additional sample of each InGaAs structure was irradiated under bias at the Jet Propulsion Laboratory's Cobalt-60 facility to a cumulative dose of 269 krad(Si) [1.04 Mrad(InGaAs)] to compare proton and gamma radiation effects.

Three samples of the Ge APD were irradiated to $2 \times 10^{12} \text{ p/cm}^2$ at UC Davis. During testing it was determined that similar changes in dark current occurred in biased and unbiased samples. Therefore, only one of the three Judson devices was irradiated under bias, using a voltage that was approximately $0.9 V_{BR}$ (mean value of 30.9V); this corresponded to a pre-irradiation gain of approximately 3. All three devices were characterized at $0.9 V_{BR}$. An additional sample was irradiated under bias using Cobalt-60 gamma radiation to a cumulative dose of 269 krad(Si) [1.01 Mrad(Ge)].

All irradiations were conducted at room temperature. Pre- and post-irradiation characterization was done at 25 °C using a thermoelectric cooler (TEC). The temperature of the TEC modules was stable to within $\pm 0.1^\circ\text{C}$. Characterizations were completed within five minutes after each irradiation to minimize annealing affects, although, in practice, measurements were very stable once the devices reached thermal equilibrium at 25 °C.

III. Results

A. Dark Current Degradation

All three near infrared APDs showed significant dark current degradation following irradiation with 63-MeV protons. Changes in dark current (ΔI_d) were linear with fluence for all three devices, but noticeable differences in damage rates were observed. Increases in dark current, compared to pre-irradiation values (I_{do}), ranged from over an order of magnitude in the Ge APD, to four orders of magnitude in the Perkin Elmer InGaAs APD (by $2 \times 10^{12} \text{ p/cm}^2$). Fig. 2 shows mean changes in dark current, as a function of fluence, for each APD. The error bars in Fig. 2 represent the standard deviation from the mean values.

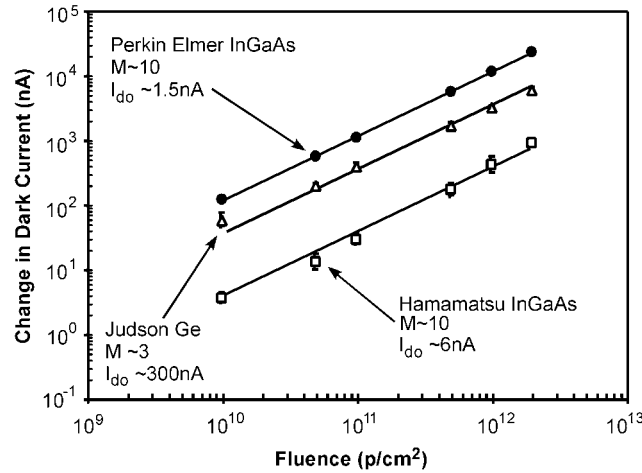


Fig. 2 Mean changes in dark current in InGaAs and Ge APDs following exposure to 63-MeV protons.

1. Hamamatsu InGaAs

The Hamamatsu InGaAs APDs had an average pre-irradiation dark current (I_{do}) of 5.6 nA (at $M = 10$). At the final cumulative fluence of $2 \times 10^{12} \text{ p/cm}^2$, the APD dark current increased to a mean value of nearly 1 μA (*an increase of over two orders of magnitude*). Changes in dark current increased linearly with fluence at a rate of approximately $4.5 \times 10^{-10} \text{ nA} \cdot \text{cm}^2 / \text{proton}$. Very little annealing was observed following irradiation. After one month of unbiased annealing at room temperature, the average reduction in dark current was only 80 nA (approximately 8 percent).

2. Perkin Elmer InGaAs

The Perkin Elmer InGaAs APD showed the highest rate of dark current degradation, at approximately $1.2 \times 10^{-8} \text{ nA} \cdot \text{cm}^2 / \text{proton}$. This rate is 26 times higher than that observed in the Hamamatsu InGaAs APD. The average I_{do} of the Perkin Elmer APD was 1.5 nA (at $M = 10$). This value increased to over 23,000 nA by $2 \times 10^{12} \text{ p/cm}^2$ – **a 4 order of magnitude increase**. The Perkin Elmer APD experienced larger recovery during unbiased annealing at room temperature than the Hamamatsu APD. Dark current values decreased by 10 percent within several hours, and by 18 percent by the eighth day after irradiation.

3. Judson Ge

The Ge APDs had a pre-irradiation dark current of 299 nA (at $M = 3$). The damage factor was $6.0 \times 10^{-9} \text{ nA} \cdot \text{cm}^2 / \text{proton}$ for this device. The mean value at $2 \times 10^{12} \text{ p/cm}^2$ was approximately 6 μA , **over an order of magnitude above the pre-irradiation value**.

4. Annealing

Unlike the InGaAs APDs, the Ge device showed quite significant annealing while unbiased at room temperature, showing a 50% reduction in dark current after several hours. Fig. 3 compares the annealing behavior of the Perkin Elmer InGaAs APD and the Ge APD. It has been noted previously that defect reordering (annealing) is dependent, among other factors, upon material type, impurity type and concentration [5]. It is likely that the material differences in the InGaAs and Ge APDs are responsible for the differences in the observed annealing trends.

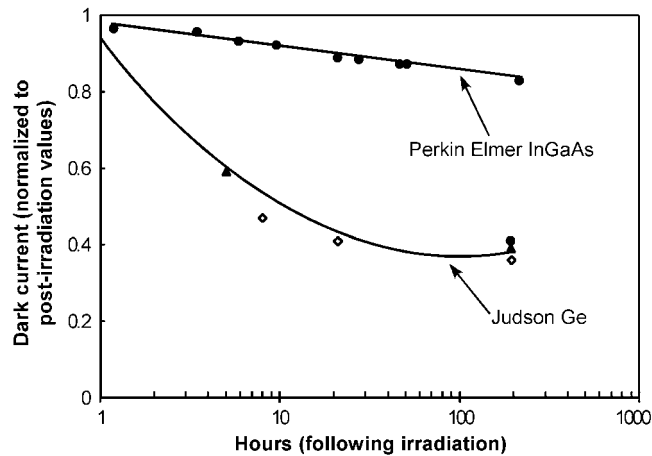


Fig. 3 Dark current reductions during unbiased room temperature annealing of the Ge and Perkin Elmer InGaAs APDs.

Table II summarizes the damage factors for the three APDs in this study.

TABLE II
NEAR INFRARED APD DAMAGE FACTORS

APD Structure	Damage Factor ($\Delta I_d/\Phi$)
Hamamatsu <i>InGaAs</i>	4.5×10^{-10} nA cm ² /p
PerkinElmer <i>InGaAs</i>	1.2×10^{-8} nA cm ² /p
Judson <i>Ge</i>	6.0×10^{-9} nA cm ² /p

B. Ionization Damage

Work with silicon APDs in FY03 [1] showed that proton-induced increases in dark current were primarily due to displacement damage in the depletion region bulk material. However, ionization damage was shown to cause increased surface dark currents in some devices, depending on the structure. This was attributed to charge trapping in the oxide between guard rings that caused surface currents to flow.

In order to determine the extent to which our 63-MeV proton results for InGaAs and Ge APDs were due to displacement damage, Co-60 gamma testing was performed in order to determine if ionization damage (and possible increased surface dark current) was a significant contributor to the overall observed dark current increases. Co-60 gamma radiation causes ionization damage, and only a very small amount of displacement damage compared to protons. It is therefore a good way to identify and isolate displacement damage vs. ionization effects that have been observed with protons. Figs. 4-6 compare 63-MeV proton and Co-60 gamma results for the near infrared APDs.

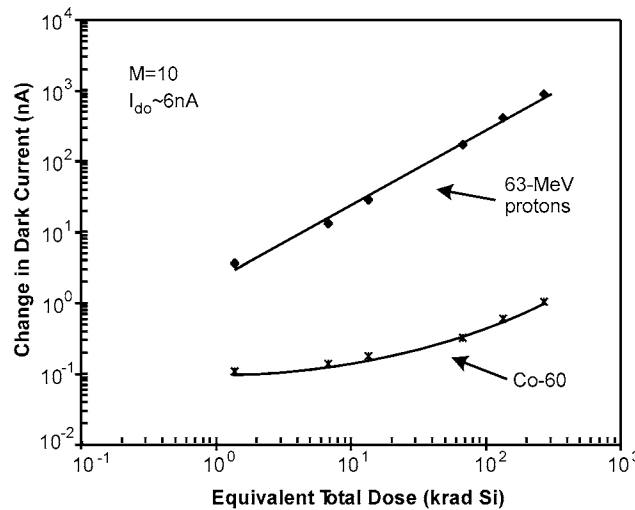


Fig. 4 Comparison of 63-MeV proton and Co-60 results for the Hamamatsu InGaAs APD.

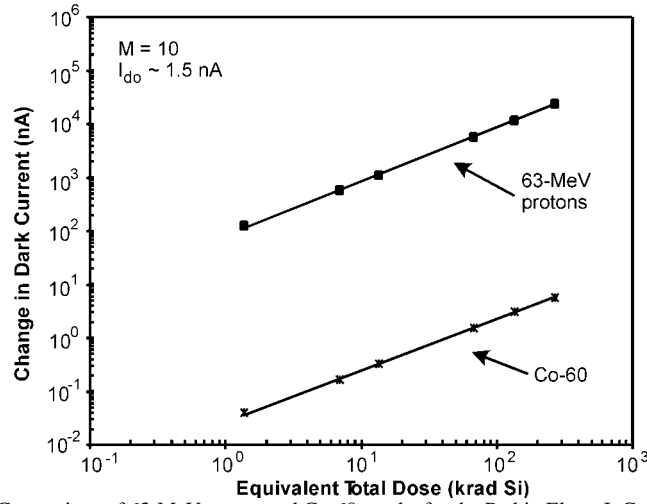


Fig. 5 Comparison of 63-MeV proton and Co-60 results for the Perkin Elmer InGaAs APD.

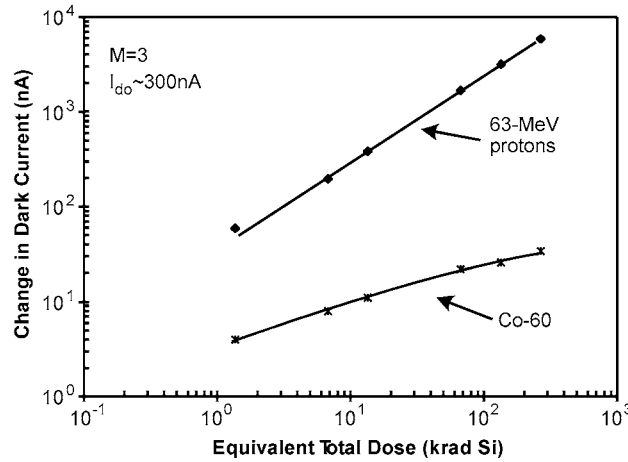


Fig. 6 Comparison of 63-MeV proton and Co-60 results for the Judson Ge APD.

When comparing 63-MeV proton and Co-60 damage, we expect that the displacement damage ratio will be related to nonionizing energy loss (NIEL), and that the displacement damage due to proton and gamma radiation will be linear with respect to fluence [6], [7]. As can be seen from Fig. 4 and Fig. 6, there is a non-linearity to the Co-60 data that indicates a total ionizing dose (TID) effect may be influencing the dark current changes in the Hamamatsu InGaAs and Ge APDs. For the Hamamatsu APD, this effect appears to saturate below 100 krad(Si)(equivalent) and may be contributing to the slight departure from linearity of the InGaAs proton data at 1 krad(Si)(equivalent). *Nevertheless, TID appears to be responsible for only a very small fraction of the total increases in dark current in all three APD technologies.*

IV. Analysis of APD Structures

In FY03, the volume of the silicon APD depletion regions was shown to correspond to the amount of displacement damage induced dark current degradation. For this reason, the structures of the near infrared APDs in this study were investigated.

A. InGaAs and Ge APD Structures

When avalanche photodiodes are operated for $M > 1$, their depletion regions contain the high field multiplication region and the deeper absorption region where photons are collected. For Ge APDs, the multiplication and absorption regions are both fabricated from Ge, while InGaAs APDs like the ones in this study use separate absorption and multiplication regions where the multiplication region is made from InP, and the active absorption region is made from InGaAs. Fig. 7 shows an InGaAs APD structure similar to the ones in our study.

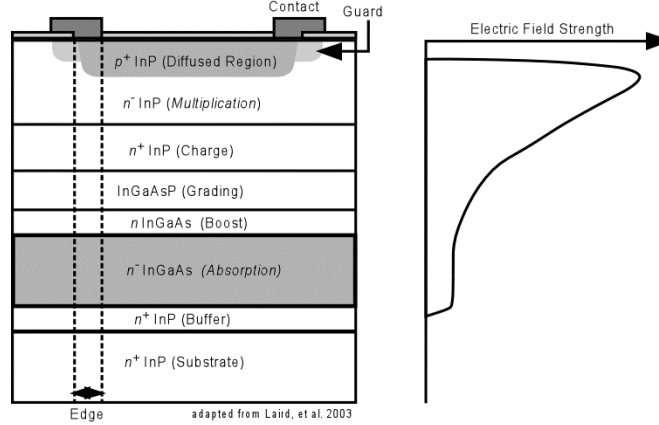


Fig. 7 Schematic of a separate absorption and multiplication InGaAs APD.

In order to achieve very high quantum efficiency, the thicknesses of photodiode absorption regions are on the order of $1/\alpha$, where α is the optical absorption coefficient. However, in order to minimize transit time effects and maximize frequency response, absorption regions are kept as narrow as possible without sacrificing too much quantum efficiency [8], [9]. InGaAs APD depletion region thicknesses from 2.5 to 7 microns are common [9], [10], and high speed Ge APDs have depletion regions ranging from several microns to over 100 microns, depending on the wavelength for which they are being optimized [8].

B. Structural Analysis

The exact structures of the APDs in this study involve proprietary information. However, in order to learn how differences in depletion region volumes could be influencing our results, focused ion beam (FIB) etching and scanning electron microscopy (SEM) analysis was performed to learn about the depletion region thicknesses. For all three APD structures FIB etching was performed to a depth of 15 microns from the surface of the active area. Electron dispersive spectroscopy (EDS) during SEM analysis of our samples allowed us to determine the elemental composition at different depths. In this way, we were able to determine the thicknesses of the InGaAs absorption regions in the Hamamatsu and Perkin Elmer APDs, and use our knowledge of the active area diameters to determine the absorption region volumes ($2,650 \mu\text{m}^3$ and $11,700 \mu\text{m}^3$, respectively). We were also able to identify guard structures in all three APDs.

The Ge APD is not a heterostructure like the InGaAs APDs, so the EDS technique could not be used to learn about the absorption region thickness of this structure. However, information about the device's spectral response allowed us to make reasonable assumptions. Although optimized for high speed at 1300 nm, the responsivity of the Ge APD at 1550 nm is about 0.9 A/W. This suggests that the active absorption depth (spanning the depletion region and deeper material where carriers are transported via diffusion) may be close to $1/\alpha$, which for Ge at 1550 nm is around 40 microns. This would make the active collection volume of the Ge APD around $314,000 \mu\text{m}^3$.

V. Interpretation of Results

The linearity of the damage in these APDs, and the absence of significant ionization damage, indicated that displacement damage in the APD bulk material was the dominant mechanism affecting dark current degradation. The increases in dark current compared to pre-irradiation values were large and varied significantly among the three studied APDs.

Displacement damage-induced dark current increases in fully depleted silicon detectors have been attributed to the introduction of carrier generation centers in the depletion regions. Such dark current increases have also been found to be directly proportional to the *volume* of the depletion region [1], [11]. Furthermore, in the case of avalanche photodiodes, carriers generated in the depletion region are eventually multiplied via the internal APD avalanche mechanism, so bulk dark current increases for APDs are also gain multiplied. The following relationship can be used to evaluate depletion region damage:

$$\frac{\Delta I_d}{V} = \frac{qn_i\phi}{2K_{gn}} \quad (3)$$

where V is the depletion region volume, n_i is the intrinsic carrier density for the detector in question, ϕ is the fluence, and K_{gn} is the damage coefficient for the material type in the depletion region [1], [11]. Analysis of the depletion region volumes *and materials* is necessary in order to evaluate our results.

A. Germanium

Using (1) while taking our approximate knowledge of the material properties of the Ge APD into account [8], and correcting for the operational APD gain, we have reasonable agreement with our results for Si APDs [1]. This allows us to be confident that the dominant mechanism responsible for the dark current degradation in the Ge APD is the introduction of carrier generation centers in the bulk material.

B. InGaAs

The complexity of the depletion regions in the InGaAs separate absorption and multiplication APDs complicates analysis of their radiation damage. We compared our InGaAs APD results to those from a recent heavy ion study by Laird et al. on a 2.5-GHz,

50 micron diameter InGaAs APD [12]. Although the focus of the study was the single event transient (SET) response of the device, analysis of dark current increases as a function of low fluence were presented. Part of that group's study involved electrical characterizations that allowed them to determine the degrees of dark current degradation corresponding to different areas within their APD. Their results showed that damage in the InGaAs absorption layer bulk material was the major contributor to dark current increases (the depth of this layer was also presented). Although also present, similar damage in the InP multiplication layer was found to be much less significant.

We compared the damage factor ($\Delta I_d / \phi$) of Laird et al. to those for the InGaAs APDs in our study by correcting for operational gain, normalizing with respect to volume, and using NIEL [7], [13] to correct for the differences in particle type between the Laird et al. study and our own. We have very good agreement, indicating that carrier generation in the InGaAs layer is responsible for the dark current degradation we observed in our InGaAs APDs.

What is interesting is that even after normalizing with respect to volume, the damage factor for the Perkin Elmer APD is nearly six times that of the Hamamatsu APD. Our work with Si APDs in FY03 revealed situations where the presence of ionization damage caused additional surface leakage current, which caused there to be a ratio between the volume-corrected damage factors of different structures. As shown above, ionization does not appear to be a factor with our InGaAs structures. Additionally, unlike the damage we have observed in the present study, the ionization damage we observed in Si APDs was almost exponential, not linear.

C. Breakdown Voltage Measurements on Perkin Elmer APD

The much higher damage in the Perkin Elmer structure spurred further investigation into the possibility that radiation-induced shifts in breakdown voltage were occurring in this device. Carrier removal in the InP multiplication layer or guard rings was considered as a possible contributor to the higher damage. Significant levels of carrier removal could change the doping profile of the lightly-doped multiplication region, causing decreases in APD breakdown voltage, or guard ring failure, which would cause runaway surface dark currents. Fig. 8 compares the dark IV curves of a Perkin Elmer sample prior to irradiation and following irradiation to $2 \times 10^{12} \text{ p/cm}^2$.

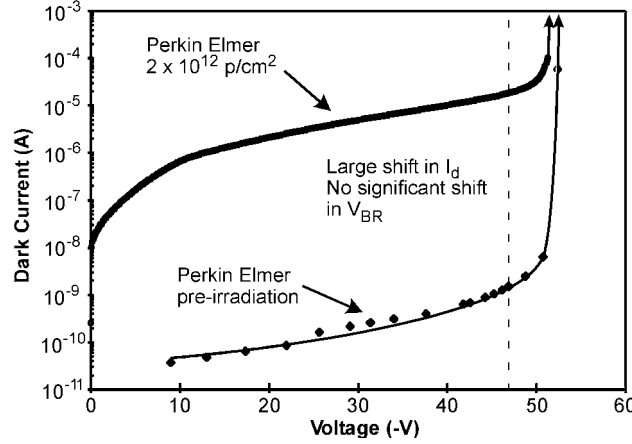


Fig. 8 Dark IV profiles of a Perkin Elmer InGaAs APD prior to and following irradiation.

Although we see the same large increases in I_d at all bias conditions as we did at the operational voltage, there was not a significant shift in breakdown voltage following the highest radiation level used in this study. Also, if carrier removal was causing a guard ring failure, we would expect the resulting increase in dark current to be abrupt after a given fluence, not linear as observed.

The stability of V_{BR} with irradiation also indicates that the APD gain is probably not being effected as we irradiate, dark current is just increasing very dramatically from the creation of carrier generation centers. *Worth noting as an important testing issue*, APD V_{BR} is usually characterized as the voltage at which the dark current is a specified amount (10 μA for our InGaAs APDs). Radiation-induced increases in dark current beyond this level at the operational voltage do not imply that a shift in V_{BR} has occurred; full IV characterization confirmed this for the Perkin Elmer device.

D. Possible Contributors to InGaAs Damage Factor Differences

Several possible contributors to the larger damage factor in the Perkin Elmer APD have been identified:

(1) Our FY03 results for Si APDs [1] showed that differences in doping appeared to contribute to differences in damage factors between structures. More highly doped depletion regions suffered higher dark current increases per unit volume, which may have been due to a higher likelihood of the creation of radiation-induced carrier generation centers in the devices with higher carrier concentration. Previous observations with Si have shown a tendency for damage coefficients to increase with carrier concentration [14]. The InGaAs absorption region of the Perkin Elmer APD may be more highly doped than the Hamamatsu APD and suffering more significant carrier generation and greater leakage current increases.

(2) It is possible that displacement damage in the InP multiplication region could have varying degrees of importance in our two InGaAs APDs. This would depend on the doping levels and volumes of the multiplication regions, and could be contributing to the differences in damage factors.

(3) Some InGaAs APDs incorporate a highly doped InP charge layer between the multiplication and absorption regions. This supports a high enough field in the InP multiplication region for avalanche to occur and a low enough field in the InGaAs absorption region to mitigate tunneling effects [15]. The presence of such a layer could contribute to additional carrier generation issues, and this could be another reason why the Perkin Elmer damage factor is high. Furthermore, if the delicate balance between the n^+ InP charge layer density and the curvature of the guard doping profile is shifted from optimal, higher gains at the periphery (“edge”) of the active volume, under the guard rings, can exceed that of the active area [12] (see Fig. 7), causing further multiplication of dark current. Carrier removal in the charge layer could tip the charge density away from optimal, causing higher dark current multiplication at the edge. It is also possible that a non-optimal balance could exist prior to irradiation. Both situations could lead to a higher damage factor.

VI. Conclusion

In FY04 InGaAs and Ge avalanche photodiodes were examined for the effects of 63-MeV protons and Co-60 gamma radiation on dark current. Although gamma radiation was not seen to cause significant changes, dark current increases due to protons were large and similar to FY03 results for silicon avalanche photodiodes, despite the smaller size of InGaAs and Ge devices. Bulk dark current increases from displacement damage in the depletion regions appears to be the dominant contributor to overall dark current degradation. Dark current in these near infrared APDs was observed to increase by one to four orders of magnitude above pre-irradiation values by a 63-MeV proton fluence of $2 \times 10^{12} \text{ p/cm}^2$.

Selection Considerations

The importance of dark current levels, before or after irradiation, depends entirely on the application and system noise requirements. For example, although even the pre-irradiation dark current is high for the Ge APD ($\sim 300 \text{ nA}$ at $M=3$), relatively high dark current and noise does not prohibit the use of an APD. In application, it is undesirable for the noise of the system amplifier to exceed the detector noise. In light of this, Ge APDs can be used in applications where amplifier noise is relatively high, in environments with high electro-magnetic interference, for example [3]. Ge APDs can also be cooled to temperatures as low as 77K to reduce dark current and noise, as is the case in photon-counting applications [16]. The order of magnitude increase in dark current by the highest fluence level is significant, although fractional dark current increases were much higher in the InGaAs APDs.

Large shifts in dark current from proton irradiation, as observed in the InGaAs and Ge APDs in this study, would be an important consideration when selecting a near infrared APD for a space based optical communications application where noise and BER are important, since increases in dark current decrease signal to noise ratio. An additional concern is that charge collection due to single event transients (SET) would be multiplied in an APD that is being utilized for high sensitivity and signal to noise ratio. Further study of the SET issue in APDs would be an appropriate area for further work.

VII. References

- [1] H. N. Becker, T. F. Miyahira, and A. H. Johnston, "The Influence of Structural Characteristics on the Response of Silicon Avalanche Photodiodes to Proton Irradiation," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 6, pp. 1974-1981, Dec. 2003.
- [2] FY03 NEPP TRO – Improved Radiation Qualification & Test Methods: Optical Detector Noise Characterization (Avalanche Photodiodes), September 2003.
- [3] G.S. Mecherle, "Fundamentals of Free Space Laser Communication," Jet Propulsion Laboratory Invited Lecture, Pasadena, CA, September 17, 2003.
- [4] W. N. Waggner, *Pulse Code Modulation Systems Design*. Norwood, MA: Artech House Inc., 1999.
- [5] J.R. Srour, C.J. Marshall, and P.W. Marshall, "Review of displacement damage effects in silicon devices," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 3, pp. 653-670, June 2003.
- [6] P. W. Marshall, C. J. Dale, G. P. Summers, and E. A. Wolicki, "Proton, neutron, and electron-induced displacement damage in germanium," *IEEE Trans. Nucl. Sci.*, vol. 36, no. 6, pp. 1882-1888, Dec. 1989.
- [7] G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, and R. J. Walters, "Damage correlations in semiconductors exposed to gamma, electron and proton radiations," *IEEE Trans. Nucl. Sci.*, vol. 40, no. 6, pp. 1372-1379, Dec. 1993.
- [8] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981.
- [9] Y. Liu, S. R. Forrest, J. Hladky, M. J. Lange, G.H. Olsen, and D. E. Ackley, "A planar InP/InGaAs avalanche photodiode with floating guard ring and double diffused junction," *Jour. of Lightwave Tech.*, vol. 10, no. 2, pp. 182-193, Feb. 1992.
- [10] K. Taguchi, T. Korikai, Y. Sugimoto, K. Makita, and H. Ishihara, "Planar-structure InP/InGaAsP/InGaAs avalanche photodiodes with preferential lateral extended guard ring for 1.0-1.6 μ m wavelength optical communication use," *Jour. of Lightwave Tech.*, vol. 6, no. 10, pp. 1643-1655, Nov. 1988.
- [11] J. R. Srour, S. C. Chen, S. Othmer, and R. A. Hartmann, "Radiation damage coefficients for silicon depletion regions," *IEEE Trans. Nucl. Sci.*, vol. 26, no. 6, pp. 4784-4791, Dec. 1979.
- [12] J. S. Laird, T. Hirao, S. Onoda, H. Ohyama, and T. Kamiya, "Heavy-ion induced single-event transients in high-speed InP-InGaAs avalanche photodiodes," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 6, pp. 2225-2232, Dec. 2003.
- [13] S. Kuboyama, H. Sindou, T. Hirao, and S. Matsuda, "Consistency of bulk damage factor and NIEL for electrons, protons, and heavy ions in Si CCDs," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 2684-2689, Dec. 2002.
- [14] J. R. Srour, S. Othmer, and K.Y. Chiu, "Electron and proton damage coefficients in low-resistivity silicon," *IEEE Trans. Nucl. Sci.*, vol. NS-22, pp. 2656-2662, Dec. 1975.
- [15] K.K. Loi and M. Itzler, "Avalanche photodetectors for 10Gb/s fiber optic receivers," *Compound Semiconductor*, vol. 6, no. 3, pp. 1-3, April 2000.
- [16] A. Lacaita, F. Zappa, S. Cova, and P. Lovati, "Single-photon detection beyond 1 μ m: performance of commercially available InGaAs/InP detectors," *Applied Optics*, vol. 35, no. 1, pp. 2986-2996, June 1996.